Small Satellite Space Operations

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ABSTRACT

CTA Space Systems (formerly DSI) has played a premier role in the development of the "lightsat" programs of the 80's and 90's. The high costs and development times associated with conventional LEO satellite design, fabrication, launch, and operations continue to motivate the development of new methodologies, techniques, and generally low cost and less stringently regulated satellites. These spacecraft employ low power "lightsat" communications (v.s. TDRSS for NASA's LEOs), typically fly missions with payload/experiment suites that can succeed, for example, without heavily redundant backup systems and large infrastructures of personnel and ground support systems. Such small yet adaptable satellites are also typified by their very short contract-to-launch times (often one to two years). This paper reflects several of the methodologies and perspectives of our successful involvement in these innovative programs and suggests how they might relieve NASA's mounting pressures to reduce the cost of both the spacecraft and their companion mission operations. It focuses on the use of adaptable, sufficiently powerful yet inexpensive PC-based ground systems for wide ranging user terminal (UT) applications and master control facilities for mission operations. These systems proved themselves in successfully controlling more than two dozen USAF, USN, and ARPA satellites at CTA/SS. UT versions have linked with both GEO and LEO satellites and functioned autonomously in relay roles often in remote parts of the world. LEO applications particularly illustrate the efficacy of these concepts since a user can easily mount a lightweight antenna, usually an omni or helix with light duty rotors and PC-based drivers. A few feet of coax connected to a small transceiver module (the size of a small PC) and a serial line to an associated PC establishes a communications link and together with the PC constitute a viable ground station. Applications included geo-magnetic mapping; space borne solid state recorder validation; global store-and-forward data communications for both scientific and military purposes such as Desert Storm; UHF transponder services for both digital data and voice using a constellation; remote sensor monitoring of weather and oceanographic conditions; classified payloads; UHF spectrum surveillance, and more. Ground processing has been accomplished by automatic unattended or manual operation. Management of multiple assets highlights the relative ease with which 2 constellations totaling 9 satellites were controlled from one system including constellation station keeping. Our experience in small end-to-end systems including concurrent design, development, and testing of the flight and operational ground systems offers low cost approaches to NASA scientific satellite operations of the 1990's.

BACKGROUND

As Congressional budgets tighten and conventional military threats appear to dissipate, private industrial R&D, universities and other potential participants in primarily LEO missions are increasingly drawn to consider new options. While

STS flight availability and piggyback experiments flown on larger missions are still possibilities, the resurgence of small satellites as viable experiment platforms is a distinct part of the general solution. This is especially so for new commercial applications and the exercise of new technologies in the space environment where time from design to launch is of the utmost importance. Five years is not the answer while two years, or less, can meet competitive and marketing needs. On the other hand, science and technology innovations are difficult to fund on their own, but can often fit nicely into multi-mission oriented lightsats.

Costs of experiments borne by "lightsats" can dip considerably below many other options, though the lightsats may not offer the same degree of reliability as their larger and costlier counterparts. Lightsats are often deployed in clusters to diminish the relative launch costs. Complementing the reductions in space segment cost, the ground segment can usually support most missions at a fraction of the expense imposed by current standards. In the past ten years CTA/SS has produced a large number of "lightsat" system designs utilizing compressed schedules for development and test and very low key mission operations. The evolution towards more automated bus, experiment and ground operations and less cumbersome spacecraft command and control is leading towards provision of stable mission operations without the customary large levels of ground support. Additionally, inexpensive space-to-end user terminals have been developed. Such services can provide direct experiment to laboratory connectivity which is of great interest in university science and engineering applications as well as commercial or government circles.

SIMPLIFICATIONS

Small satellites with small budgets for operations must still satisfy broad requirements:

- Provision for bus control via ground commanding
- Provision for experiment/payload control
- Provision for onboard telemetry collection of both bus and experiment/payload systems
- Provision for on-board autonomous health and stability protection
- Provision for TT&C data flows and experiment/payload data flows

In the most common instance, mission operations are performed from a central location where the state of health (SOH) of the entire spacecraft is continuously assessed. It is generally here also that flight commands are issued to the spacecraft. In CTA Space Systems' history, we have built and operated the first GLOMR satellite in 1985 from a PC but without any automation of communications. Telemetries (TTMs) were received and commands sent aloft from an inexpensive adjunct transceiver module under micro-control and employing a simple roof-mounted UHF omni-directional antenna. Command streams were short and TTMs limited in this spacecraft, but for those that followed, there were many improvements and adaptations stemming from a growing assortment of mission requirements. It is important to embody certain "simplifications" into the fabric of the overall system design in order to facilitate low cost, yet reliable, small satellite operations.

We seek to accomplish certain key objectives:

1. Operate experiments from pre-established command sequence files
2. Provide pre-uplink command verification
3. Employ macro style bus and experiment commands
4. Provide spacecraft scheduled (i.e., for future) as well as immediate command execution options
5. Provide reliable (error free) and autonomous communications
6. Provide "intelligent" SOH displays/reports
7. Provide key mission operations software elements as part of the EGSE (avoiding full

probably separate efforts) and use throughout I&T (Integration and Test), the IST (Integrated Systems Test) and Environmental Testing
8. Offer autonomy in routine communications scheduling
9. *Wherever possible encourage provision of experiment autonomy with independence of other experiments and bus*
10. *Wherever possible use autonomous bus sub-systems (notably ADACS) requiring minimal ground attention*

Item (1) is tried and true through such programs as STACKSAT (three satellites: TEX, POGS & SCE); SCSC (two satellites known as "MACSATS" and seven "MICROSATS); REX; and RADCAL. The savings and reliability associated with the construction and pre-validation of operational sequences which make up mission operations segments are very significant. For example, a series of commands required to operate a diffusion pump and to trigger a particular set of experiment actions is accomplished by writing a series of commands under software control. Each individual command is range-checked and otherwise evaluated to be a valid command (as noted in item 2) and is encapsulated in a 16-bit check sum (CRC) to assure future integrity. The set of commands is saved as a file and can be evoked during all phases of ground-based testing as a block with individual command execution times shifted by a definable increment avoiding having to make up sets with specific pre-set execution times. The same segment can be conveniently recalled and sent to the spacecraft when on-orbit. The very significant work force necessary to conduct around the clock environmental and integrated systems tests is greatly reduced by *avoiding* the effective hand entry of large numbers of detailed commands. Errors are nearly eliminated in the process. Item (3) is a significant objective in that it suggests that wherever feasible, the ground to space interface is held to as simple a structure as possible. That is, the spacecraft bus or experiment/payload commands should be process-oriented if possible. For example, in the case of the preparation of an instrument application, there may be a 25 step timed sequence of "micro style" commands required. If the controller for that experiment or the bus processor can maintain that sequence as part of its operational flight code, then all the ground team needs to do is to evoke that process by a simple command such as "Experiment 2, Process 5, ON=2/23/95 13:00:00." Similarly the shutdown might be commanded "Experiment 2, Process 6, ON=2/23/95 13:45:00." These two commands are easy to deal with and will achieve the highest level of reliability. If this is not possible, then the command sequence file approach can be used instead with the operator simply evoking the two procedures adjusting the process execution times according to the plan. The disadvantage here is that there are now many commands to uplink and it is essential that they are *all* accounted for on the spacecraft prior to beginning the execution of the procedure. Verification of the presence of the entire *command chain* for a process in the past has usually been accomplished by a satellite schedule dump and on the ground review. The operator then had the option to re transmit missing commands or to delete commands. A better method involves the addition of a special command type that will inhibit execution of incomplete command streams. This command spawns a notification message to the ground that its powers have been evoked and that the sequence is either incomplete or OK. With present and emerging powerful and robust flight digital electronics including wide usage of EDAC RAM or other (nearly) non-volatile mass memory, storage of command chains onboard that can be evoked by an immediate or future-acting ground uplink command are more prevalent.

Normally commands are sent to the spacecraft in advance of planned execution and are executed at future times under the action of the spacecraft's software scheduler. Immediate commands (with zero tokens for execution date/time) are, however, allowed to execute immediately. Given that the uplink commands and downlink TTMs/data are reliably communicated, there is little in the area of routine flight operations that necessitates constant operator attention much less "crisis-like" circumstances on the ground. Indeed, with easily interpretable and "to the point" SOH displays available on the ground, the missions are virtually made to "fly themselves" for considerable periods of time.

Item (7) represents an important ingredient to planning and executing a successful low cost small satellite mission. It is a standard practice at CTA/SS to develop the TTM and command formats and specifications early in the systems design stage and to build around them the essentials of ground station processing and communications software. These elements are assembled into the PC-based EGSE suit that accompanies the satellite from the I&T test bed, throughout I&T and environmental testing and beyond. These *same* elements which have accumulated much equivalent "flight time" and have been perfected in a natural manner are then incorporated into master or remote ground station packages. There is no separate team associated with the ground station operational software; it is basically an inherited evolute of the spacecraft development process.

Point (8) suggests an innovation that is currently underway in three CTA/SS programs. Unlike older systems that require scheduling and pre-programming of satellite communications events, some new programs are now operating via intelligent space and ground systems to totally avoid routine contact scheduling which is a tedious process. The UTs, for example, maintain their own ephemerides and simply come on the air when the satellite is known to be visible at some preset minimum elevation angle and/or in an allowed azimuth band. In some programs the satellite itself autonomously contacts ground units without cumbersome deterministic scheduling uplinked previously by the master controller. Not only is this much more efficient, it also allows dynamic response disallowed by too much pre-planning.

The final two points refer to spacecraft subsystem and experiment levels of autonomy and non-mutual interference. A very great deal of labor and engineering efforts are expended throughout testing and later mission operations; labor that escalates sharply when systems conflict in any way or when excessive and too-frequent monitoring and control is required. This placing the operators "in-the-loop" in the manner of a very stiff control law. Building inexpensive space systems for small satellites that do not impose these penalties may be a challenge, but should always be entertained in both the bus and experiment arenas.

SMALL SYSTEMS, SMALL OPERATIONS APPROACH

A Case Study: POGS

The typical lightsat ground configuration consists of a frequency agile UHF transceiver with mod/demod capabilities in various forms of BPSK and FSK modulations operating under a simple micro controller. This unit can be rack mounted inside, or configured in an environmental housing for exterior deployment. Coax connects the RF to a RHC or LHC circular polarized omni-directional radome-covered antenna or complementary pair. From the transceiver unit there is a standard serial (RS-232) line interfacing an ordinary PC. This comprises the minimal standard configuration. A variant is the replacement of the omni-directional antenna is a light weight directional antenna which may be either linearly or circularly polarized, but in either case can be driven by inexpensive light duty commercial rotors. Such directive antennas are driven by open-loop controllers connected via PC cards implants or via an additional PC RS-232 serial ports. A component of the ground station software generates antenna tracking data for each pass and provides it to the antenna controller. While there is nominally only a few dB's of gain advantage, it is often useful in noisy metropolitan areas and the same system can also lead a high gain X-band antenna, for example, to acquire the satellite and allow it to switch to closed-loop tracking for more precise alignment.

A typical mission illustrates the major points in CTA/SSs small systems approach. The USAF STACKSAT mission deployed three small satellites into nominal 300 nm polar orbits. POGS (Polar Orbiting Geomagnetic Satellite) was dedicated to the primary NORDA mission of magnetic mapping of the Earth's field and was equipped with a 6 foot boom-mounted NASA magnetometer instrument and a 4 Mbit CMOS dual channel SSR (solid state recorder). To prepare the operational staff of a one or two individuals from Bay St. Louis, a two week long training program was conducted in McLean. Shortly thereafter, and while the future operators looked on, CTA/SS conducted the initial on-orbit testing procedures which commenced with the deployment of the spacecraft's gravity-gradient boom equipped with hysteresis rods to quench spin and libration. With the boom and antennas deployed, the satellite was ready for checkout and the entire procedure was handled from a PC system with omni antenna from the rooftop of our building just outside the Washington Beltway at Tyson's Corner Virginia. Despite high local noise levels various sources including one nearby arc-welder, everything went smoothly and the spacecraft was soon ready for hand-off. Operations had consisted first of a mission plan previously approved by the USAF and Aerospace. The plan permitted sufficient latitude thus avoiding serious delays while necessary variations would have been proposed and officially accepted. This is important to the low profile operation that we designed and budgeted. Finally the station at the user site at Bay St. Louis took over the operation that included two key unmanned high latitude receiving sites. Data down linked from POGS was automatically diverted to a WORM optical disk drive occasionally removed and mailed to the Bay. St. Louis facility although data was frequently recovered remotely via a dial-up link. Software updates and parameterization changes were facilitated via the remote dial-up link which also allowed operators at either Bay St. Louis or CTA/SS to "man" the remote station. This also allowed one to see all the displays and to operate the keyboard remotely as though present on-site. POGS provided its requisite magnetic data in a few months and is still operating after about four and a half years. POGS also has a number of communications capabilities and other sensors all of which have performed flawlessly and have been operated with the most minimal of ground support.

Communications scheduling for all ground elements and the spacecraft is handled over intervals of generally ten days time by the Bay St. Louis PC from which the appropriate files are simply "modemed" into the remote Arctic sites. The uplink to the satellite of command files can be accomplished from any of the three stations. Multiple sites provide excellent redundancy although the avoidance of non-standard computers, other equipment and software always provides inexpensive and obtainable components which need not be duplicated as spares. This approach permits a natural flow of technology improvements to the ground systems. It hinges on the use *wherever possible* of commercial software and hardware products and the use *where possible* of standard interfaces. This is not generally true of government systems.

Highlights of Cost Reducing Factors

- Relaxed Official Coordination/Documentation Requirements
- Technical Backup Availability Including On-Line Operational Support
- Spacecraft Supports Long Term Scheduling to Allow Autonomous Operation of *Both* Bus and Experiments for Days or Weeks on End

- Semi- or Fully-Automated Ground and Spacecraft Communications Scheduling Software
- Compact and Powerful Spacecraft Commands
- Telemetries and Telemetry Displays Keyed to Early Warnings via Color Coding at the Top Level
- Use of COTS (Consumer Off The Shelf) Products:
  - ◊ Generic IBM-like PCs and Peripherals
  - ◊ Land-Based Communications
  - ◊ Standard File Transfer (e.g., KERMIT)
  - ◊ Operating Systems (space and ground)
  - ◊ Use of Standard Protocols (HDLC[space-ground], TCP/IP[Internet], etc.)
- Planned Software Reusability
- Training and Simple SOPs (Standard Operating Procedures)

FUTURE IMPROVEMENTS

As small satellites (nominally of Class C construction) improve and advance with continuing miniaturization/weight reduction and other technical innovations, inclusion of new technologies and science applications are bound to create enhanced demands. Obtaining high cost-to-effectiveness for many future missions will depend on successes in modifying conventional approaches to today's large scale expensive launches and flight operations. These changes may be perceived as somewhat radical today, and yet to a large extent, they represent a rebirth of older principles of pioneering space developments that, over the years, have become somewhat anachronistic. The procurement process for DoD and NASA and associated regulatory demands are simply not structured to foster the rapid development of small satellite missions (including inexpensive LVs). To an extent they may also appear to conflict with STS mission elements since many tasks have and continue to be executed by manned crews- tasks that for a fraction could be carried out *not for days but for years* by small satellites linked to inexpensive ground systems and targeted to the needs of the experimenters/laboratories. Conventional approaches to flight operations are grand by comparison to the probable minimal needs of many potential candidate packages. To regain the spacecraft "pioneering" spirit of the '60s using today's small powerful computers both onboard and on the ground together with spectrum of technology improvements in both materials, components, structures, and manufacturing processes we can achieve magnitudes more results for the same relative costs.

A major and bold new NASA initiative is fully targeted towards achieving the goals and objectives typified by the small satellite mission under discussion in this article. The **Small Spacecraft Technology Initiative (SSTI)**, dubbed "pathfinder" by the program sponsor, will produce two spacecraft "LEWIS" and "CLARK" with the latter being built by CTA/SS with Martin Marietta utilizing a set of IPDTs (Integrated Product Development Teams) including commercial entities, universities, NASA research centers and others involved with technology and science infusion/assessment and in fostering US commercialization efforts. CLARK is a fast track 24 month-to-launch program lofting a 3-meter optical imaging payload, a variant of the successful MAPS instrument ("μMAPS"), an X-Ray Spectrometer, an Atmospheric Tomography Retro-reflector while also incorporating 36 explicit advanced technologies for space testing. Major bus elements including the 32-bit RHC3000 processor and SOA ADACS components offer unique opportunities to combine otherwise independent activities to provide enhancements in both science results and in operational efficiencies. The use of the μMAPS to detect clouds and prevent down link of useless images is but one example. NASA has adopted the entire tenant of the small satellite mission- form initial design and development, through launch and initial orbit, and throughout the flight. All of the concepts advanced in this paper are included in the CLARK plan which will allow the enhancement previously tested equipment, software and operational methodologies in an expanded context enveloping the disbursement of larger volumes of experiment data and in the promulgation of other mission information utilizing more open Internet accessways to facilitate wide community participation in this interesting endeavor. The low cost of the entire mission makes necessary the reforms cited and includes the active participation of the NASA sponsor as an IPDT member and not as an outside force passing judgment based on periodic reviews. SSTI significantly *is* an Initiative and will add impetus to future small satellite programs. In this sense the moniker "Pathfinder" seems most appropriate.

Systems Development

1. Architectural Approaches

* *Presented in Poster Session*

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